AEROSPACE BATTERY ACTIVITIES AT NASA/GODDARD SPACE FLIGHT CENTER

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Prelude

- Identify the Maturity of a Rechargeable Secondary Battery Cell Chemistry for Aerospace Use
- Test and Validate the Matured Cell for Aerospace Application
- Design, Test, Qualify and Infuse the Advanced Battery into Spacecraft
- Manage on board Battery Operation for a Successful Mission
- GSFC "Pioneered" Rechargeable Secondary Battery for Aerospace Application since early 1960

Battery Chemistry

- Nickel-Cadmium (NiCd) Battery
- Nickel-Hydrogen (NiH_2) Battery
- Lithium-Ion (Li-Ion) Battery

NiCd Battery

- Conventional
  - Gates Aerospace Batteries
  - SaFT
  - ACME
- Super
  - Hughes Aerospace/Eagle Picher Technologies

NiCd Battery Conventional - cont'd.

- Gates Aerospace Batteries
  - 1 to 50 Ah
  - Design, Test, Infuse and Use
  - Low-Earth-Orbit (LEO), Geosynchronous-Earth-Orbit (GEO), Libration Point
  - Over 80 Spacecraft over 40 years
    - LANDSAT (22 plus years) and ERBS (19 plus years) batteries have the longest onboard LEO life

NiCd Battery Conventional - cont'd.

- SaFT
  - 40 Ah
  - Design, Test, Infuse and Use
  - LEO and GEO
    - TDRS
    - POES
    - FUSE

NiCd Battery Conventional- cont'd.

- ACME
  - 6.5 Ah
  - First LEO Application
  - Design, Test, Infuse and Use
  - LEO
  - CHIPSAT

Super NiCd Battery

- Hughes/Eagle Picher Technologies
  - 9 to 50 Ah
  - Design, Test, Infuse and Use
  - LEO
    - SMEX (5)
    - XTE
    - TRMM
    - Image
    - TOMS
    - NEAR
    - Contour

Major Current NiCd Battery Flight Project

- **POLAR ORBITAL ENVIRONMENTAL SATELLITE (POES) : N'**
  - Additional spacecraft is in consideration
    - Possible delay in NPOES launch
  - Requirements
    - 3 SAFT batteries, 17 40Ah NiCd cells in series per battery
    - LEO/Polar
    - 2 years (Design), 3 years (Goal)
    - 0 to 21% Depth-of-Discharge (DoD), 5°C
  - Launch is scheduled for December 2007

NiH_2 Battery

- Individual Pressure Vessel (IPV)
- Common Pressure Vessel (CPV)
- Single Pressure Vessel (SPV)
- All from Eagle Picher technologies except as indicated

NiH_2 Battery - cont'd.

- IPV
  - 50 to 160 Ah
  - Design, Test, Infuse and Use
  - Advanced Catalytic Wall Wick Application
    - TERRA, LANDSAT, AQUA, AURA AND NPOES
  - Both LEO, GEO and Libration Point
    - First LEO Application (HST)
    - First In-Orbit Refurbishment (HST)
  - TERRA
  - LANDSAT
  - AQUA
  - TDRS (Boeing)
  - GOES (Boeing)
  - TIMED
  - AURA
  - SWIFT
  - NPP
  - NPOES
  - GLAST

NiH_2 Battery - cont'd.

- CPV
  - 16 Ah to 40 Ah
  - Design, Test, Infuse and Use
  - GOES Project Funded the 16 Ah Development
  - MAP Developed 23 Ah with Bypass Circuitry
  - Both LEO, LEO and Libration Point
    - SSTI
    - MAP
    - ICESAT
    - MESSENGER
    - STEREO

NiH_2 Battery - cont'd.

- SPV
  - 12 Ah to 40 Ah
  - Design, Test, Infuse and Use
  - HQ Funded 20 Ah Development
  - LEO
    - Glory

Major Current NiH_2 Battery Flight Projects

- GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE (GOES) : N - Q
- HUBBLE SPACE TELESCOPE (HST)
- OTHERS

GOES

- GOES-N, O, P; GOES-N Launch 1/06
- Requirements
  - 1 Battery, 24 cells/Battery, 123 Ah, <75 % DoD nominal during maximum eclipse, safehold DoD <94%
  - Launch with ~65% State-of-Charge (SoC)
  - GEO for 10 years, -10 to 15°C
- Cell and Battery Status
  - IPV, Boeing (Hughes); Eagle Picher Technologies, Colorado Springs (N&O) and Torrance (P)
  - One battery per S/C with three packs in series; each pack consists of eight cells in series
  - GOES-N/O flight lot activation in 3/04; cells for GOES-O were placed in cold storage after activation and cell acceptance testing
  - GOES-P flight lot built (3/03) were placed in dry storage until needed
  - GOES-N, battery were installed on S/C in 9/04
- Issues/Concerns
  - Qualification of Torrance and Extended dry and wet storage of cells
  - Ground handling of charged batteries at launch site and Lack of cooling at launch site
  - Temperature differences between battery packs during ground operations, orbit raising, and on-orbit operations
  - Cell Imbalance and Cell Leak or Short

HST

- Tentative Battery Change-out for Servicing Mission 4
- Requirements
  - 6 Batteries (22 Cells/Battery, 80 Ah NiH_2) and 1 Spare Battery
  - LEO, 5 years design (32,000 cycles) w/ 10 years goal (64,000 cycles), <10% DoD, -5 to 5°C
- Cell and Battery Status
  - Rabbit-ear, Man-tech Design
  - 26 cells (13 each from lot 10 and lot 11) activated in 96. Nominal 2 years stress test performance, six 5-cell pack system test at MSFC completed 2000 successful cycles (apparent poor load sharing and cell voltage divergence due to cell heritage, cell lot and some questionable cells)
  - 13 cells (7 from lot 10 and 6 from lot 11) activated in 98. Nominal 8000 stress cycles and subsequent 3000 mission profile cycles
  - Activated remaining dry stored (in cold) flight cells in 8/00, stress test completed 9000 nominal cycles
  - 7 batteries built and finished battery level ATP at Joplin, completed in 4/02
  - Assembly, test, and delivery of 2 modules and spare battery to GSFC in 10/02
  - 2 flight battery modules and 1 spare battery in storage (0°C ± -5°C) at GSFC
- Issues/Concerns
  - Proper storing of the batteries at launch site and wet-life

Major Current NiH_2 - Others

- AIM (9/06)
- STEREO (8/06)
- GLAST (07)
- GLORY (07)
- NPP (08)
- NPOES (13)
- JWST (13)

Li-Ion Battery

- Emerging Technology
  - High specific energy
  - High energy density
  - Benign handling requirements compared to Nickel Chemistry
- Concerns
  - Overcharge
  - Cell Balancing
  - Cycle Life
  - Calendar Life and Solstice Storage
- Mitigation
  - Started Cell Test Program in late 02
  - Selected Vendors
    - Japanese Storage Batteries (JSB)
    - AEA Technology Battery Systems Ltd. (ABSL)
    - saFT
    - Lithion
    - Quallion

Li-Ion Battery - Test Profile

- Low-Earth-Orbit (LEO)
  - Temperature: 20 ± 2°C
  - Depth of Discharge: about 30%
  - Discharge: Constant current for 36 minutes
  - Charge: Constant current to a battery voltage clamp with taper for 60 minutes
- Low-Lunar-Orbit (LLO)
  - Temperature: 20 ± 2°C
  - Depth of Discharge: about 30 or 40% (twice a year 80%)
  - Discharge: Constant current for 48 minutes (160 minutes for 80% DoD)
  - Charge: Constant current to a battery voltage clamp with taper for 65 minutes
- Geosynchronous-Earth-Orbit (GEO)
  - Temperature: 20 ± 10°C
  - Eclipse Period: 42 days, Discharge at 0.6 C for a maximum shadow period of 72 minutes, Charge at C/20 to a battery voltage clamp with taper for the remainder of duration
  - Solstice Period: 140 days, battery voltage maintained at a battery voltage clamp (~70% SoC)
  - Prior to each eclipse season, the battery is charged up to 100% SoC using C/20 charge rate to battery voltage clamp with taper

Li-Ion Battery - LEO Test Data

Vendor	Battery Size (Ah)	Start Date	Clamp Voltage (V)	EoD [a] Voltage (V)	Cycle #
ABSL	60	2/03	33.6	29.2	6000*, [b]
JSB	100	5/03	31.6	28.6	14,500
SaFT[c]	80	11/03	31.2	27.7	10700**
Lithion	100	1/04	7.8***	7.14****	8750

*	First 1800 cycles at 40% DoD
**	12 cycles at 27 %, and 32 cycles at 13% DoD
***	31.2 V at battery level
****	28.56 V at battery level
a	End-of-Discharge (EoD)
b	The testing stopped due to gradual failure of strings (total six(6)) after 2250 cycles at 30% DoD - ABSL attributed this to the effect of the short that occurred after 30% DoD 900 cycles
C	Cell balancing circuit

Li-Ion Battery - LLO Test Data

Vendor	Battery Size (Ah)	Start Date	Clamp Voltage (V)	EoD Voltage (V)	Cycle #
ABSL[a]	60	1/05	33.6	30.8	4000
JSB[b]	50	2/05	31.6/32*	28.75	3200
SAFT[b]	40	2/05	31.2/32.8*	28.1	3400
Lithion[b]	50	4/05	15.8/16.4*, **	14.1***	2600
Quallion[b]	15	2/05	31.6/32.8*	28.2	3400

* 2nd voltage clamp used prior to 80% discharge cycle, all batteries completed at least one 80% DoD cycle

** 31.6/32.8 V at battery level

*** 28.2 V at battery level

a 30% DoD

b 40% DoD

Li-Ion Battery - GEO Test Data

Vendor	Battery Size (Ah)	Start Date	Clamp Voltage (V)	EoD Voltage at Maximum DoD (V)	Shadow Period
ABSL	80	2/03	33.6	27.5	5
JSB	100	5/03	16.0*	14.8***	5
SAFT[a]	80	11/03	32.8	28.0	4
Lithion	100	1/04	8.2**	7.1****	4

*	32.0 V at battery level
**	32.8 V at battery level
***	29.6 at battery level
****	28.4 at battery level
a	Cell balancing circuit

Major Current Li-Ion Battery Flight Projects

- NEW MILLENNIUM PROGRAM (NMP)
  - Space Technology - 5 (ST-5)
- SOLAR DYNAMIC OBSERVATORY (SDO)
- LUNAR RECONNAISSANCE ORBITER (LRO)
- OTHERS

NMP : ST-5

- February 2006 Launch
- Requirements
  - 1 Battery, 7.5 Ah
  - Elliptical, sun synchronous orbit with some moon eclipses, 3 months duration, less than 400 cycles, up to 60% DoD, -10 to 40°C
- Cell and Battery Status
  - 1 Test Battery, 1 Qual. Battery, and 3 Flight Batteries
  - Awarded contract to ABSL in 01
  - 6 parallel-strings each containing 2 1.5 Ah SONY cells in series
  - Prototype battery delivered, testing completed
  - Battery successfully completed qualification testing and delivered in 5/02
  - I&T have been supporting spacecraft operations through environmental testing
  - Flight batteries (1 for each of 3 spacecraft) successfully completed acceptance testing; delivered to GSFC in 7/03
  - Discharged batteries stored in cold
- Issues/Concerns
  - Charging during short sunlight periods

SDO

- August 2007 Launch
- Requirements
  - 1 Battery, 800 cells (100 parallel strings of 8 cells in series)/Battery, 120 Ah
  - GEO, 5 years goal (approx 400 cycles), 60% max. DoD, 10 to 30°C
- Cell and Battery Status
  - 1 Test Battery, 1 Qual. Battery, and 2 Flight Batteries
  - ABSL selection and award announced in 8/05
  - Design discussions and test program Completed in 9/05
  - Design Conformance Review in 1/06
- Issues /Concerns
  - Overcharge
  - Range safety requirements

LRO

- October 2008 Launch
- Requirements
  - 1 Battery, 80 Ah
  - LLO, 14 months (about 6,000 cycles), nominal 30% DoD and a few 80% DoD, 10 to 30°C
    - Goal 5 years at reduced DoD
- Cell and Battery Status
  - Li-Ion Chemistry is base lined due to mass constraints
  - 1 Qual. Battery, 1 Test Battery, and 2 Flight Batteries
  - Released Request for Proposal in 12/05
  - Proposals are due in 1/06
- Issues and concerns
  - Schedule
  - Cell balancing methodology for parallel/series cell configuration
  - Overcharge

Major Current Li-Ion - Others

- Cream (05 on)
- Calipso (06)
- THEMIS (8/06)
- GPM (12))
- LISA (12)
- HST (12)?
- MMS (13)
- JWST (13)?

NASA/GODDARD SPACE FLIGHT CENTER (GSFC) Spacecraft

Spacecraft	Launch Date (s)	Orbit (km X km) and Inclination	Cell Type	Battery Size	Batterty/Cell Manufacturer
LOFTI-1	2/61		3.5 Ah, Cyl.		Sonotone
Explorer VI	8/59		F Cell, **Cyl.	14 Cell	Sonotone
Explorer XXII (S-66)	10/10/64	LEO, 106 m, 1075X887, 79.7^0	F Cell, **Cyl.	23 Cell	Sonotone
Ariel I	4/26/62	LEO, 95.9 m, 770X361, 53.8^0	6Ah, Prismatic	2 - 10 Cell	Gulton (1^{st} Pris.)
Telstar I	7/62	LEO, 157.7 m, 5642X944, 44.8^0	5 Ah, Cyl.	1 - 19 Cell	Bell Labs/ Gould
Telstar II	5/7/63	LEO, 225 m, 10,800X971, 42.7^0	5 Ah, Cyl.	1 - 19 Cell	Bell Labs/ Gould
Alouette I	9/29/62	LEO, 105 m, 80.4^0	5 Ah, Cyl.	6 - 12 Cell	Sonotone
Syncom I II III	2/14/63 7/26/63 8/19/64	GEO, 33.5^0 GEO, 38.6^0 GEO, 6^0	6 Ah	2 22Cell	Gould (Same as Above)
Nimbus I	8/18/64	LEO, 94.4 m, 602X387, 98.7^0	4.5 Ah Prismatic	7 23 Cell	RCA-Astro/ Sonotone
Nimbus II	5/15/66	LEO, 108 m, 1182X1096, 100.4^0	4.5 Ah Prismatic	8	RCA-Astro/ Sonotone

NASA/GSFC Spacecraft (cont'd)

Spacecraft	Launch Date(s)	Orbit (km X km) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
OAO-A1 OAO-A2 OAO-3	Apr 66 12/7/68 8/21/72	LEO, 100 m, 750X750, 35^0 (nominal)	20 Ah Prismatic	3 22 Cell	Grumman/Gulton
OSO-I	3/7/62	Leo, 95.2 m 595X553, 32.8^0	12 Ah	2	Ball Bros.
SAS-A SAS-B	12/12/70 11/16/72	LEO, 96 m, 3.0^0 LEO, 95 m, 1.9^0 (550X550)	6 Ah	1 8 Cell	APL/Gulton APL/GE
ATS-F (6)	5/30/74	GEO, m, $1\text{-}6^0$	15 Ah	2 - 19 Cell	Fairchild/Gulton
TIROS –1 2 3 4	4/1/60 11/60 6/61 2/62	LEO, 99 m, 738X689, 48.3^0 . .	F Cell ** Cyl.	3 21 Cell	GE-Astro/ Sonotone
TIROS –5 6 7 8	6/62 9/62 6/63 12/63	LEO, 955X591, 58.1^0	F Cell ** Cyl.	3 21 Cell	GE-Astro/ Sonotone
TIROS –9 10	1/65 7/2/65	LEO, 2581X705, 96.3^0 LEO, 835X741, 98.6^0	F Cell ** Cyl.	3 21 Cell	GE-Astro/ Sonotone

NASA/GSFC Spacecraft (cont'd)

Spacecraft	Launch Date(s)	Orbit (kmXkm) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
NOAA-1, (ITOS-A) 2 3 4 5	12/11/70 10/72 11/73 11/74 7/76	LEO, 115 m, 1472X1492, 101.9^0	6 Ah	2 23 Cell	RCA Astro/G.E.
NOAA-A NOAA-6…11	6/79…9/88	LEO, 115 m, 1472X1492, 101.9^0	26.5 Ah	2 17 Cell	RCA Astro/G.E.
Landsat –4 5 D	7/16/82 3/84 7/82	LEO, 98.6 m, 7070X683, 98^0	50 Ah	3 22 Cell	MDESC/GAB
COBE	11/89	LEO, 900X900, Sun Synchronous	20 Ah	2 - 22 Cell	MDESC/GAB
SMS-1 (A) 2(B)	5/17/74 2/6/75	GEO, 21.8 h, 1.8^0 GEO, 23.9 h, 0.1^0	3 Ah	2 20 Cell	Ford/EPI
GOES-1, SMS-C 2 3	10/75 6/77 6/78	GEO, 24.05 h, 1.0^0	3 Ah	2 20 Cell	Ford/EPI
GOES-C	8/80	GEO, 24.05 h, 1.0^0	6 Ah	2 - 27 Cell	Hughes/GE
GOES –…10		GEO, 24.05 h, 1.0^0	12 Ah	28 Cell	Loral/GAB

NASA/GSFC Spacecraft (cont'd)

Spacecraft	Launch Date(s)	Orbit(km X km) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
IUE	1/26/78	HEO, 23.9 h, 45469x25722, 28.6^0	6 Ah	2 17 Cell	GSFC/GE
SMM	Feb 80	LEO	20 AH	3 - 22 Cell	MDESC/GE
TDRS-A…D (4)	4/83…3/13/89	GEO	40 Ah	3 - 24 Cell	TRW/GE
HCMM (AEM-A)	4/26/78	LEO, 96.7 m, 646x558, 97.6^0	9 Ah	1 21 Cell	Boeing/EPI
SAGE	2/18/79	LEO, 96.7 m, 661X548, 54.9^0	9 Ah	1 21 Cell	Boeing/EPI
GRO	4/5/91	LEO, 445X459, 28.5^0	50 Ah	6 * - 22 Cell	MDESC/GAB
UARS	Sep 91	LEO, 6000x600, 57^0	50 Ah	3 * - 22 Cell	MDESC/GAB
EUVE		LEO, 528X528, 28.5^0	50 Ah		MDESC/GAB
TOPEX	Aug 92	LEO, 1336X1336, 66 (Frozen Orbit)	50 Ah	3 * - 22 Cell	

NASA/GSFC Spacecraft (cont'd)

Spacecraft	Launch Date (s)	Orbit (km X km) and Inclination	Cell Type	Battery Size	Batterty/Cell Manufacturer
ERBS	Oct 84	LEO, 610X610, 57^{o}	50 Ah	2 - 22 Cell	MDESC/GAB
SAMPEX	July 1992	LEO, 550 X 675, 82^{o}	S, 9 Ah	1 - 22 Cells	Hughes/EPI
FAST	August 1996	350 X 4200, 8 ^{o}	S, 9 Ah	1 - 22 Cells	Hughes/EPI
SWAS	Dec. 1998	LEO, 600 Km Circular, 70^{o}	S, 21 Ah	1 - 22 Cells	Hughes/EPI
WIRE	March 1999	LEO, 470 X 540, 97.4^{o}	S, 9 Ah	1 - 22 Cells	Hughes/EPI
TRACE	April 1998	LEO, 600 X 650, Sun Synchronous	S, 9 Ah	1 – 22 Cells	Hughes/EPI
EO - 1	Nov. 2000	LEO, 705 km Circular, Sun Synchronous	S, 50 Ah	1 –22 Cells	Hughes/EPI
RXTE	Dec. 1995	LEO, 600 Km Circular, 23^{o}	S, 50 Ah	2 – 22 Cells	Hughes/EPI
TRMM	Nov. 1997	LEO, 405 Km Circular, 35^{o}	S, 50 Ah	2 – 22 Cells	Hughes/EPI
TOMS	July 1996	LEO, 500 km Circular boosted to 740 km, Sun Synchronous	S, 9 Ah	1 – 22 Cell	Hughes/EPI
GGS - WIND	Nov. 1994	L2	26.5 Ah	3 – 16 Cells	
GGS - POLAR	Feb. 1996	51,000 X 5,100, 86^{o}	26.5 Ah	3 – 16 Cells	

NASA/GSFC Spacecraft (cont'd)

Spacecraft	Launch Date (s)	Orbit (km X km) and Inclination	Cell Type	Battery Size	Battery/Cell Manufacturer
MAP	June 2001	GEO, L2	23 Ah NiH2	1 - 22 Cells CPV, 11 Modules	EPT
AQUA	May 2002	705 Km, Circular, Sun Synchronous, 98°	160 Ah NiH2	1 –24 Cells	EPT
TERRA	Dec. 1999	705 Km, Circular, Sun Synchronous, 98°	50 Ah NiH2	2 – 54 Cells IPV	EPT
LANDSAT 7	April 1999	705 Km, Circular, Sun Synchronous, 98°	50 Ah NiH2	2 – 17 Cells	EPT
HST	April 1990	600 Km, 28.47°	80 Ah NiH2	6-23 Cells	EPT
ACE	August 1997	Libration	12 Ah	1-18 Cells	GAB/SAFT
FUSE	1999	LEO	40 Ah	1-22 Cells	SAFT

Notes:

* Consists of one or more Modular Power Systems (MPS). Each MPS contains three (3) 50 Ah, NiCd batteries.

** Sonotone's cylindrical F cell was typically rated at 5 Ah.

S Super NiCd, no designation means conventional NiCd

Summary

- Goddard Space Flight Center has "Pioneered" Rechargeable Secondary Battery Design, Test, Infusion and In-orbit Battery Management among NASA Installations
- Nickel-Cadmium Batteries of various Designs and Sizes have been Infused for LEO, GEO and Libration Point Spacecraft
  - Over 18 years of mission life for LANDSAT (22 plus), ERBS (19 plus) and IUE batteries
  - Disabled and subsequently in-orbit stored ERBS battery was brought into service (adventure!!!) to gather important ozone data (the only satellite, at that time, that could gather this information)
  - Mr. Goldin, then NASA Administrator, credited GSFC for the Super NiCd battery development and for the infusion of the technology into the NASA missions

Summary - cont'd.

- Nickel-Hydrogen Batteries have Currently been Baselined for Majority of our Missions
  - HST is the first LEO application, and the onboard batteries have the longest (16 years) LEO cycle life
  - Advanced features were first implemented in onboard LANDSAT batteries
  - Designed and developed 16 Ah CPV battery
    - MARS missions benefited
  - MAP 23 Ah CPV battery design was adopted for missions like MESSENGER, STEREO etc.
  - 20 Ah SPV battery design is qualified for two year LEO missions
    - Glory spacecraft battery adapted the design

Summary - cont'd.

- Li-Ion Batteries from ABSL, JSB, SAFT and Lithion have been Designed and Tested for Aerospace Application
  - Emerging Technology for future NASA Missions
  - Completed two plus years of Real Time LEO and GEO cycles
  - ST - 5, a four-month mission, will be our first Li-Ion application and first application of ABSL batteries in America
  - Baselined for SDO (GEO) and LRO (LEO)
    - Life (Cycle and Calendar), solstice charge mode and cell balancing in a battery are the major issues flying the Li-Ion technology
  - ST-5, Calipso and THEMIS that are scheduled for launch in 06 would provide valuable in orbit battery performance experience and the lesson learned would be implemented in the future Cell/Battery Designs, Battery Ground Handling, and the onboard Battery Management